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Surface morphology of active normal faults in hard rock: Implications for the mechanics of the Asal Rift, Djibouti

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ABSTRACT

Tectonic-stretching models have been previously proposed to explain the process of continental break-up through the example of the Asal Rift, Djibouti, one of the few places where the early stages of seafloor spreading can be observed. In these models, deformation is distributed starting at the base of a shallow seismogenic zone, in which sub-vertical normal faults are responsible for subsidence whereas cracks accommodate extension. Alternative models suggest that extension results from localised magma intrusion, with normal faults accommodating extension and subsidence only above the maximum reach of the magma column. In these magmatic rifting models, or so-called magmatic intrusion models, normal faults have dips of 45–55° and root into dikes. Vertical profiles of normal fault scarps from levelling campaign in the Asal Rift, where normal faults seem sub-vertical at surface level, have been analysed to discuss the creation and evolution of normal faults in massive fractured rocks (basalt lava flows), using mechanical and kinematics concepts. We show that the studied normal fault planes actually have an average dip ranging between 45° and 65° and are characterised by an irregular stepped form. We suggest that these normal fault scarps correspond to sub-vertical *en echelon* structures, and that, at greater depth, these scarps combine and give birth to dipping normal faults. The results of our analysis are compatible with the magmatic intrusion models instead of tectonic-stretching models. The geometry of faulting between the Fieale volcano and Lake Asal in the Asal Rift can be simply related to the depth of diking, which in turn can be related to magma supply. This new view supports the magmatic intrusion model of early stages of continental breaking.

1. Introduction

Tectonic-stretching models have been previously proposed to explain the process of continental break-up through the example of the Asal Rift (Djibouti). In this kind of models (e.g., Dunbar and Sawyer, 1989; Jackson and McKenzie, 1983; Kusznir et al., 1991; Lin and Parmentier, 1990), the normal faults are considered a secondary consequence of stretching, which controls the deformation associated with upwelling of hot viscous material. As extension proceeds, the brittle zone of the crust is chopped up by multiple generations of normal faults that form at high angles, rotate to lower angles, and are subsequently cut by new high angle faults (e.g., Jackson and McKenzie, 1983; Tapponnier and Francheteau, 1978). Because of their low angle fault plane, the normal faults accommodate the subsidence and the extension of the crust.

In the Asal Rift, this mechanism is in agreement with the presence of sub-vertical normal faults at the surface, and with the results of 3D spatial distribution of seismicity beneath the Asal Rift (Doubre et al., 2007a,b). These results propose lower dips (50–60°) for the faults located far from the rift central axis, and vertical dips for the normal faults bounding the rift inner floor. However, the seismicity beneath the Asal Rift does not seem related to vertical fault planes, but associated with nucleation/opening of tensional fractures (Aki, 1984; Doubre and Peltzer, 2007; Shimizu et al., 1987) around the volume of hot rocks (see the discussion in this paper). Moreover, this mechanism implies normal fault blocks tilted away from the rift axis. Restoration of the Asal Rift topography (De Chabalier and Avouac, 1994), paleomagnetic evidence (Manighetti, 1993), and basalt flows vectors (Stieltjes, 1980) rule out this assumption, the current slopes of the topographic surface being inherited from the initial shape of a central volcano, the Fieale (De Chabalier and Avouac, 1994).

Models of ground deformations (e.g., Stein et al., 1991; Tarantola et al., 1979, 1980), associated with the 1978 seismo-volcanic event (e.g., Abdallah et al., 1979; Lépine et al., 1980), require the presence of dikes beneath the Asal Rift. Down to the brittle/ductile zone, the vertical component of displacement (subsidence), which cannot be accommodated by dikes, would be accommodated by sub-vertical normal faults. The horizontal component of displacement (extension), which is accommodated at depth by cracks filled by magma (dikes), is

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accommodated near the surface by open cracks. This geometry seems in agreement with the current surface observations that suggest sub-vertical normal faults and open fissures, and it is also used to explain the long-term evolution of the Asal Rift (Cattin et al., 2005; De Chabalier and Avouac, 1994; Stein et al., 1991). In these tectonic-stretching models applied to the Asal Rift, the slip on normal faults is not correlated with a dike intrusion, but controlled by the foundering of blocks into the lithosphere.

Alternative models (Fig. 1B) suggest that most of the deep extension results from localised magma intrusion, with faults accommodating extension and subsidence above the maximum reach of the magma column (e.g., Abelson and Agnon, 1997; Agnon and Lyakhovsky, 1995; Buck, 2006; Hubert-Ferrari et al., 2003), which is proposed for Afar in a model combining geophysical and petrological data (Fig. 1B; Pinzuti et al., 2007a). In magmatic rifting models, or so-called magmatic intrusion models, the yield stress is reduced by an order of magnitude (e.g., Buck, 2004, 2006) compared to the tectonic-stretching models (e.g., Dunbar and Sawyer. 1989; Jackson and McKenzie, 1983; Kusznir et al., 1991; Lin and Parmentier, 1990). In these models, the normal faults result from dike intrusion, which impose a dipping plane of 45°–55° to the normal faults (e.g., Agnon and Lyakhovsky, 1995), as is also suspected beneath the Asal Rift, where the current horizontal extension (measured across the opening faults from InSAR data) suggests that the sub-vertical faults at the surface have shallower dipping planes at depth (Peltzer and Doubre, 2006). To link the surface observations of the Asal Rift with dipping normal fault at depth, this fault geometry implies some slip partitioning (Bowman et al., 2003), with opening cracks accommodating part of the extension and normal faults accommodating subsidence and the remaining fraction of extension.

While these two models can lead to the same observations of sub-vertical faults and opening cracks at the surface, the magmatic intrusion model contributes to sub-vertical scarps, which are due to slip partitioning, that turn to dipping normal faults at depth and that root into dike intrusions. This study aims at 1) proposing, from morphology of exhumed normal fault in hard rock, a new conceptual model of normal fault evolution due to magmatic intrusion, and 2) exploring the consequence of this model for the long-term evolution of the Asal Rift, by linking the suspected geometry of normal faults at depth with magma intrusion.

2. Geological setting

The Asal rift is the first emergent segment of the Aden ridge, which propagates westward on land into the Afar depression (Fig. 2A) (e.g., Manighetti et al., 1998). With a ~40 km length, whose 15 km are emerged, it currently opens at 16 ± 1 mm yr^{-1} in the N40° ± 5°E direction (Fig 2A and B). This rift is structured by a dense network of fissures and sub-vertical normal faults with throws up to 200 m, propagating northwestward (N130° ± 10°) from the Ghoubbet Bay to the northwest shore of the Lake Asal (Fig. 2B; Manighetti et al., 1998).

Asal Rift opening is characterised by effusive events associated with incipient rifting (Richard, 1979) from 853 ± 35 ky to 315 ± 53 ky (Manighetti et al., 1998). While immerged context allows the formation of hyaloclastites (326 ± 15 ky) in the south part of the rift, magmatic activity remains effusive in the north (315 ± 53 ky and 334 ± 43 ky; Manighetti et al., 1998). From the end of this period until ~100 ky, the evolution of the rift is characterised by the activity of a central volcano, the Fieale (Fig. 2), which fills the inner floor and conceals previous faults with large volumes of basalt lava flows (Pinzuti, 2006; Pinzuti et al., 2007a). Around 50 ± 20 ky, magmatic activity decreases and the whole successive basalt lava flows that structure the Fieale volcano become gradually offset by normal faults (Manighetti et al., 1998). The structure of the modern rift starts 40–30 ky ago, with the development of the border faults H and α1 (Fig. 2; Stein et al., 1991; Manighetti et al., 1998; Pinzuti, 2006; Pinzuti et al., 2007b). From this period, the Fieale volcano progressively collapses and the magmatic activity locates within the inner floor along small volcanic edifices and eruptive fissures (Fig. 2; Stein et al., 1991; De Chabalier and Avouac, 1994; Manighetti et al., 1998; Doubre et al., 2007b).

The latest magmatic episode recorded in the rift corresponds to a seismic-volcanic sequence (Mb: 5 and 5.3) that occurred in 1978 (Abdallah et al., 1979; Lépine et al., 1980). This event produced ~2 m of extension in a N40° direction, and up to 70 cm of subsidence in the inner floor (Ruegg et al., 1979). A one-week basaltic fissural eruption, generated at the northwestern tip of the volcanic chain, gave birth to the Ardoukoba volcano (Fig. 2B; Allard et al., 1979). Currently, the most important deformations are observed around the Fieale edifice and the northeast part of the rift (Doubre and Peltzer, 2007; Doubre et al., 2007a,b; Manighetti et al., 1998; Peltzer and Doubre, 2006).

3. Data acquisition

To examine competent rocks, which can sustain open fissures to a substantial depth, we studied massive rock types corresponding to basalt. We measured 14 vertical topographic profiles along 4 of major normal faults of the Asal Rift, which offset successive basalt lava flows of 1 to 5 m thick along their traces (Fig. 3A). Profiles were obtained using a handheld laser distance metre and angle measuring binoculars to determine baseline distance, horizontal distance and height for each point (Fig. 3B). The instrumental error associated with the measurements is smaller than 50 cm, which is less than the typical "raggedness" of fault scarps. It should be noted that this technology

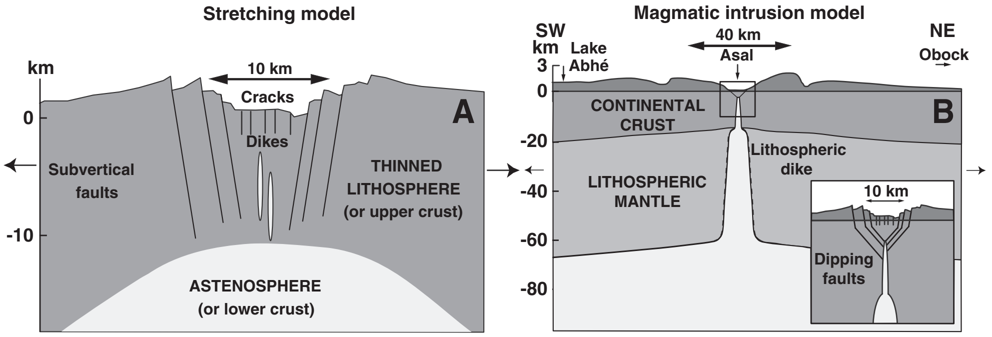

Fig. 1. A) Schematic representation of models of rift evolution dominated by ductile stretching at the base of the lithosphere or within the lower crust. Steeply dipping faults accommodate subsidence controlled by distributed ductile deformation at depth. Ductile deformation is assumed to occur at depths of a few kilometres. B) Localised deformation extending through the crust and mantle. The model shown is based on Pinzuti et al. (2007a), which combined seismic refraction, seismological, gravimetry (Berckhemer et al., 1975; Knox et al., 1998; Makris and Ginzburg, 1987; Nyblade et al., 2000; Ruegg, 1975) and petrological data (Pinzuti, 2006; Pinzuti et al., submitted for publication). Note the two figures are not at the same scale.